# Increased pressure from rising bubbles as a mechanism for remotely triggered seismicity

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AFTERSHOCKS of large earthquakes tend to occur close to the main rupture zone, and can be used to constrain its dimensions. But following the 1992 Landers earthquake (magnitude $M_w = 7.3$) in southern California, many aftershocks were reported[1] in areas remote from the mainshock. Intriguingly, this remote seismicity occurred in small clusters near active volcanic and geothermal systems. For one of these clusters (Long Valley, about 400 km from the Landers earthquake), crustal deformation associated with the seismic activity was also monitored. Here we argue that advective overpressure[2-7] provides a viable mechanism for remote seismicity triggered by the Landers earthquake. Both the deformation and seismicity data are consistent with pressure increases owing to gas bubbles rising slowly within a volume of magma. These bubbles may have been shaken loose during the passage of seismic waves generated by the mainshock.

Hill et al.[1] describe the seismicity following the Landers earthquake in southern California on 28 June 1992 and show that seismicity levels were higher in a number of regions (all with volcanic history) remote from the Landers mainshock. One is the Long Valley caldera, which has a variety of instrumentation in place because of continuing concern about a possible

eruption[8]. Langbein et al.[8] model ground surface motions during 1989–91 in terms of increased pressure in a spherical source at 7-km depth under the resurgent dome together with growth of a dyke (vertical magma-filled opening) under Mammoth Mountain. These changes resulted in increased seismicity, although the spatial distribution suggests a more complex geometry than in the simple model. Figure 1 shows maps of the Long Valley caldera comparing the seismicity in the 5 days before the Landers earthquake with that in the 5 days after it. Also shown are the sites of a Sacks–Evertson borehole strainmeter[9] (POP), a long-baseline tiltmeter[10] (LBT) and the proposed pressure sources of Langbein et al.[8]. The triggered seismicity has an areal distribution, and magnitudes and depths, similar to those of earthquakes occurring usually in this region[1]. The obvious inference is that the triggered seismicity is due to the same process that drives the continuing seismicity, except that after the Landers earthquake the process was enhanced.

Figure 2 shows the cumulative seismicity at Long Valley together with the dilatation at POP and the east–west tilt at LBT (similar plots of seismicity and dilatation were shown in Hill et al.[1]). We see the clear correlation between the rapid increase in the cumulative number of earthquakes over about 4 or 5 days and the increase in contraction at POP as well as the change in tilt at LBT. Suggested mechanisms for the remote triggered seismicity include hydraulic pumping of high-pressure pore fluids[1], relaxation of partially crystallized magma bodies[1], enhancement by fault connectivity of static strain[11] and aseismic slip triggered by dynamic strain[12,13]. None of these suggested mechanisms can adequately explain either the duration of the triggered activity or the form of the deformation transient. Here, as it seems clear that the continuing seismicity results from increased pressure in magma under Long Valley, we look for an explanation of the triggered seismicity in terms of a process which increases that pressure, resulting in the observed deformations and the increase in seismicity.

We consider the advective overpressure mechanism[2,5] as a viable candidate. Our attention was drawn to this by Sahagian and Proussevitch[6,7], who showed that if a bubble of perfect gas rises in an incompressible liquid inside a rigid sealed container,

the pressure throughout the liquid will increase by $\rho g h$, where $\rho$ is the liquid density and $h$ the height through which the bubble rises. They suggested that this process might be a mechanism for producing increased pressure in a magma chamber; for example, for a 1-km vertical rise, the increase in pressure for the ideal case would be $\sim 30$ MPa (300 bar). A simple allowance for compressibility of rock and magma ($dV/V = dp/\kappa$, where $\kappa$ is incompressibility) indicates a pressure increase lower than for the ideal case by a factor of about 3. This factor will depend on the shape of the magma body, but the sparsity of our observations precludes more than qualitative considerations; we restrict our analysis to a feasibility study. Previous work[8] demonstrates the existence of pressure sources (magma bodies) but does not clearly resolve the geometry of these sources. We note that an increase of a few megapascals in a shallow dyke under Mammoth Mountain would result in the observed dilational stain at POP and roughly one-third of the east–west tilt at LBT (the additional tilt may be due to small pressure increases in the closer, deeper sources); bubbles rising less than 1 km could produce such changes. Such small pressure increases are consistent with a lack of observable changes in the line lengths[1] ($<\sim 1$ mm) monitored (see ref. 8 for locations; MILL sub-net was not occupied) during the days following Landers. Thus, this mechanism passes the first test, that it be capable of producing deformations consistent with the observations.

Next we consider how this process could be initiated. The deformation changes began when the seismic waves generated by Landers passed through the area. Perhaps during the rarefaction stages of the waves, the pressure in the magma is lowered sufficiently for dissolved gas to form bubbles throughout the magma. We reject this as a significant source as such a process would result in a relatively large and instantaneous increase in pressure; such a pressure increase would be observable as a rapid change in dilatation at POP (such rapid tilt at LBT would not necessarily be detected because of acceleration effects of local microseismic activity). More likely is the release of pre-existing bubbles that are held down by surface tension effects. These bubbles will exist because as magma previously rose from greater depths through a series of narrow conduits (cracks), the pressure decreased and dissolved gases formed small bubbles[14 16]. Entry into the magma body is presumably though a highly fractured region in which these small bubbles can be captured at the abundant solid surfaces. Bubbles that are marginally held down (vertical force balance) may readily be shaken loose by the movement of the magma induced by the seismic waves, because Landers was a source of high-amplitude, long-period waves[1]. An indication of the size of such bubbles can be obtained by considering the vertical force balance on a bubble adhering to a flat horizontal surface. This is a balance between the upthrust due to buoyancy and the downward component of the surface tension forces. The net vertical downward force may be written $F = 2\pi\gamma r \sin^2\alpha - 2\pi\rho g r^3 (2\cos^3\alpha + 3\cos^2\alpha - 1)/6$, where $\gamma$ is the surface tension, $\alpha$ the half-angle of the cone subtended at the
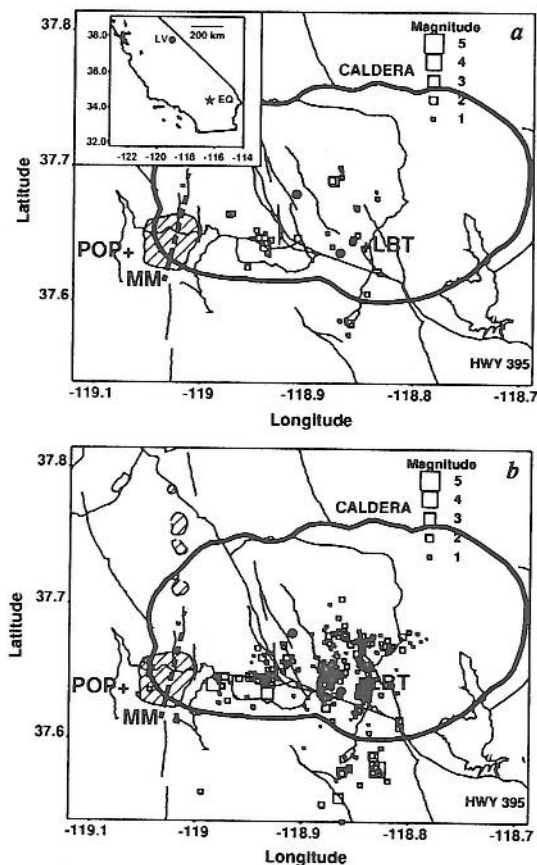


FIG. 1 Map of Long Valley caldera area showing seismicity 5 days before (a) and 5 days after (b) Landers. The insert map in a shows part of California and the locations of Long Valley (LV) as a solid circle and of the Landers earthquake (EQ) as a star. The caldera maps shows the locations of the borehole strainmeter (POP) and long-baseline tiltmeter (LBT). Solid circles and heavy dashed line indicate the locations[3] of the magma deep pressure source and dyke, respectively; the two deep source locations were determined for different time intervals. The Inyo Domes are shown with diagonal hatching; MM, Mammoth Mountain. The seismicity patterns are suggestive of a magma source with complex geometry.
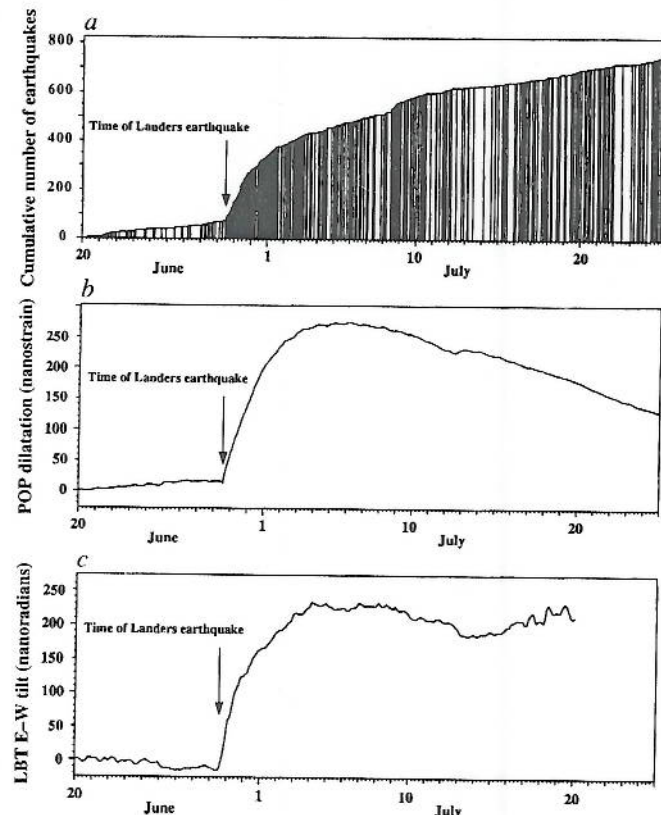


FIG. 2 a, Cumulative number of earthquakes in the Long Valley caldera area; b, dilatation (contraction positive) at POP; c, east–west tilt at LBT. The rapid increase in the rate of earthquake occurrence corresponds closely to the increase in contraction and tilt. North–south tilt has a similar shape to the east–west tilt, but with lower amplitude. Seasonal strain changes at POP preclude knowledge of the extent of recovery at POP; initial slow tilt-recovery seems to have been interrupted on 12 July by a nearby deformation event which also shows as a small positive excursion on POP.

centre of the bubble by the circle of contact, $r$ is the radius of the bubble and $\rho$ is the density contrast between magma and gas. The first term is due to surface tension and the second is the Archimedean upthrust on a truncated spherical bubble (for $\alpha = 0$, it reduces to the standard expression for a wholly immersed spherical bubble). This second term gives an upward force for small $\alpha$ and is zero for $\alpha = 60°$. For greater values of $\alpha$, a bubble of any radius will experience a net downward force. Magma densities and surface tensions do not depend strongly on the magma chemistry[17], so the balance condition is primarily a function of $r$ and $\alpha$. Bubbles with radius $\sim 5$ mm will be marginally stable for small $\alpha \sim 5°$.

The increases in contraction at POP and in the seismicity occur over an interval of $\sim 4$ d. Thus, for the advective overpressure mechanism to be significant the bubbles must be able to rise vertically less than 1 km during that time. For our purposes, Stokes' law may be written $r^2 = 9h\eta/2gt\rho$, where $r$ is the radius of a bubble that will rise through a vertical height $h$ in time $t$ for a liquid of viscosity $\eta$ and density contrast $\rho$. Figure 3 shows, as a function of viscosity[11], the size of bubble that will rise 1 km in 4 days. Magma composition in the area is likely to be either basaltic or rhyolitic[18]. For a basaltic magma we see that bubbles $\sim 1$ cm in diameter released from near the bottom of the chamber would be able to increase the pressure on a timescale which matches the change in strain and tilt and the increase in seismicity rate. As indicated above, bubbles of that size would be held down marginally with very small angles of contact. The period of roughly 4 days during which contraction increases is then a natural consequence of the ascent velocity of sub-centimetre-size bubbles. Smaller bubbles rising as aggregates (with higher velocities than isolated bubbles[19]) would also be consistent with such timescales. That the strain rate decreases during this time is also reasonable: there is likely to be a size distribution of bubbles; larger ones will get to the top sooner and then the pressure increase rate will decrease; the effective viscosity higher in the chamber may well be higher (leading to slower ascent velocities) because of lower temperature and/or partial crystallization.

The initial rapid (4 d) increase in seismicity is followed by a return to the background rate over an interval of a few tens of days. Whether or not this was accompanied by deformation recovery is unclear. The tilt record (Fig. 2) does not show significant recovery; the dilatation record has been adjusted by removal of an estimated seasonal change and the uncertainty in this procedure precludes reliable knowledge of dilatation recovery. After the Landers earthquake there was an increase in

$^3$He/$^4$He in gas discharged from a fumarole near Middle Mountain[20] which would be consistent with increased loss of gas from the magma reservoir. Even if there is no recovery in deformation, we expect that the seismicity rate would return to the earlier value as this is characteristic of aftershock activity, which decreases with time although coseismic static deformations persist.

We have shown here that advective overpressure due to rising gas bubbles is a viable model to explain the remote triggered seismicity in the Long Valley area following the Landers earthquake. In contrast to previous suggestions[1,10,12], the time variations of the seismicity and deformations are a simple consequence of the mechanism producing the excess magma pressure. Many of the other sites of triggered seismicity may have magma chambers[1] and we suggest that this mechanism could be the general explanation for the triggered seismicity following the Landers earthquake. □

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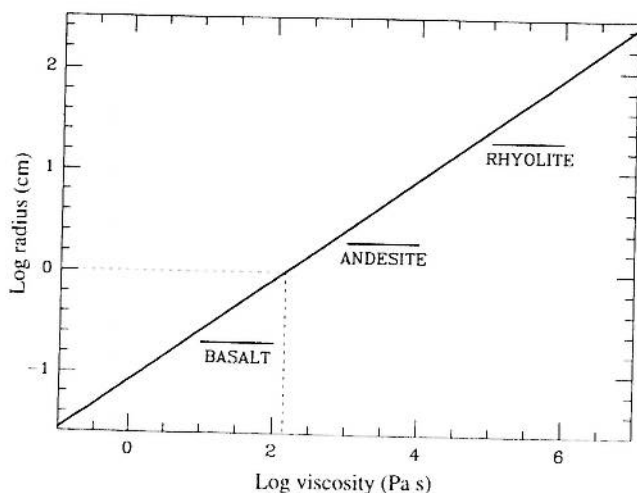
FIG. 3 Plot based on Stokes' law showing size of bubble that would rise 1 km in 4 days as a function of viscosity. For a basaltic magma, such bubbles would have a size of a few millimetres (dashed lines).